Passive Localization of Multiple Sources Using Widely-Spaced Arrays with Application to Marine Mammals

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LONG-TERM GOALS

The goal of our research is to develop systems that use a widely spaced hydrophone array to localize and track multiple unknown sources, possibly in shallow-water environments, over long distances. The long-term goal is to contribute to the behavioral ecology of marine mammals by simultaneously tracking multiple vocalizing individuals in space and time.

OBJECTIVES

The objectives of this project are: (i) Development of new theoretical frameworks for localization of underwater sound sources using widely spaced hydrophones; (ii) Testing and fine-tuning of the theory and its implementation through simulations; and (iii) Application to whale data collected on widely spaced hydrophone arrays, including Navy ranges such as at the Pacific Missile Range Facility (PMRF) and the Atlantic Undersea Test and Evaluation Center (AUTEC).

APPROACH

We cooperate on all aspects of the research. Currently one of us (Nosal, a PhD candidate) spends 80% of her time on this project, and the other (Frazer, a professor) spends 20% of his time on it.

To localize underwater sound sources, we first create a three dimensional grid of candidate source locations. The response at each of the hydrophones is modeled by assuming the source is at one of the candidate source locations. Acoustic propagation models are used as necessary. The modeled responses are compared to the measured responses to get a likelihood value for the current grid point. This is repeated for every grid point to get a likelihood volume, which takes its maximum at the estimated source location.

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14. ABSTRACT
The goal of our research is to develop systems that use a widely spaced hydrophone array to localize and track multiple unknown sources, possibly in shallow-water environments, over long distances. The long-term goal is to contribute to the behavioral ecology of marine mammals by simultaneously tracking multiple vocalizing individuals in space and time.

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Various approaches and tricks are used for different problems:

1. It is not always necessary to use all of the response information. For example, sperm whales vocalize in deep water and emit very loud, broadband, impulsive clicks. In this case, it may be sufficient to use direct arrival times only, which gives very fast run times.

2. Additional information (such as amplitudes, phases, and surface/bottom reflections) is used as required for increasingly difficult problems (such as with fewer receivers, increasing noise levels, more sources, non-impulsive sources).

3. Our pair-wise waveform (PWW) processor is used to deal with the unknown source waveforms.

4. Our pair-wise spectrogram (PWS) processor extends the PWW processor by using spectrograms instead of waveforms. Spectrograms allow us to use high frequencies, which are sensitive to environmental mismatch and noise.

5. To reduce computational requirements, we use multi-step processes that gradually refine position estimates by using increasingly fine grid spacing.

WORK COMPLETED

We developed and implemented a localization method that relies exclusively on the delay between the directed and surface-reflection arrivals (the DRTD method). It was successfully applied to a dataset from the AUTEC range in the Bahamas to track a sperm whale using 5 bottom mounted hydrophones for 25 minutes. That work was reported in a paper in *Applied Acoustics*.

The DRTD method was improved and combined with a method that uses the time of direct arrivals (the DRTD/TOA method). This was used to re-process the AUTEC sperm whale data and to obtain time and position estimates for every sperm whale click in the dataset. These estimates were used to develop a method to estimate the orientation (roll, pitch, and yaw) of the sperm whale, and to recover the beam pattern of sperm whale clicks. These methods and results were presented at the Winter 2006 meeting of the *Acoustical Society of America* and are in press in a paper in the *Journal of the Acoustical Society of America*.

The PWW and PWS processors were developed and implemented. Due to high computational demand, our implementations were parallelized for use on supercomputers. Simulations were run for numerous environments and source/receiver configurations. The theory and initial simulations were published in the Winter 2006 *Oceanic Engineering Society Newsletter*. We modified the PWW and PWS processors to reduce computational requirements (run-times are reduced by a factor equal to the number of hydrophones). These modifications are presented in a paper (in press in the *IEEE Journal of Oceanic Engineering*) along with additional simulations and processor performance comparisons with a time of arrival method and the Bartlett processor. The PWS processor was applied to the same AUTEC sperm whale dataset as above to give the same track. Although this dataset does not highlight the strengths of the PWS processor (multiple, unknown, continuous wave sources in shallow water), it provided a successful first validation of the algorithm and its implementation. The comparisons were presented at the *3rd International Workshop on Detection and Localization of Marine Mammals using Passive Acoustics*.

RESULTS

While most localization methods rely on accurate synchronization of receiver clocks, the DRTD method can be used to accurately determine source positions despite receiver timing offset. This is useful for estimating and correcting for receiver timing offset using sources of opportunity. This advantage was emphasized during the *2nd International Workshop on Detection and Localization of Marine Mammals*, during which groups using time difference of arrival methods could not localize the sperm whale source because of a 2.34 s receiver timing offset [Adam *et al.* 2006]. The DRTD method yielded an accurate whale track, which was similar to the track found by other groups after the timing offset had been discovered [Adam *et al.* 2006]. Figure 1 shows a 3D display of the resulting track.

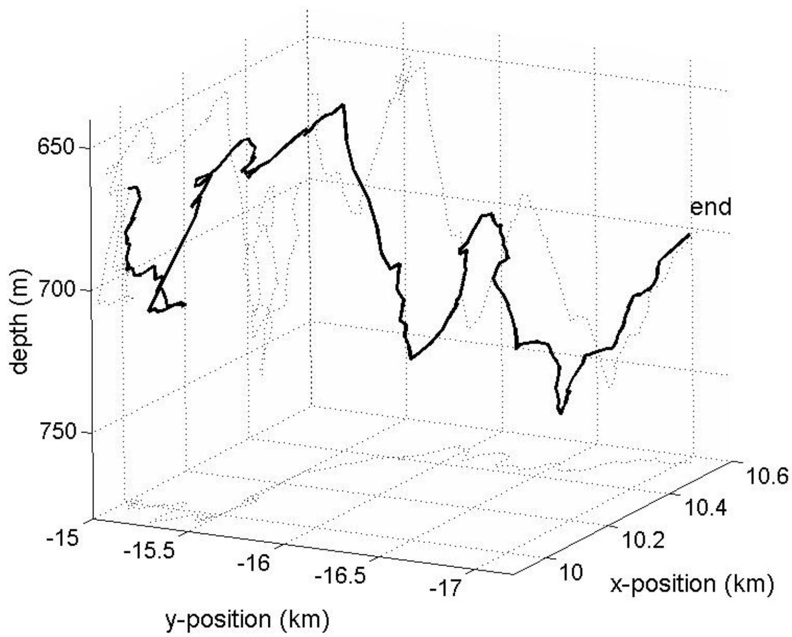

Figure 1. Three dimensional track of a sperm whale localized using the DRTD method and 5 bottom-mounted hydrophones in the AUTEC range. The track represents 25 minutes of data. Projections onto the three planes are shown with dotted lines.

The DRTD/TOA method can give very precise position and source generation time estimates in real-time. For the sperm whale above (5 bottom mounted hydrophones with ~5 km spacing), the DRTD/TOA method estimates positions to within 20 m, and click times to within 0.1 ms (95% confidence intervals). The high precision of these times and positions can be used to recover animal orientation (pitch, roll, and yaw) and beam patterns (Figure 2). Source levels can also be recovered if receiver sensitivity is known.

In simulations with environmental mismatch, noise, and multiple animals with long duration calls, PWS processing outperforms all other methods. Comparisons of a time of arrival method, and the

Bartlett (linear matched-field), PWW, and PWS processors are shown in Figure 3. Additional simulations have shown that varying PWS processor parameters (such as the size of windows used to create spectrograms) optimizes the tradeoff between processor resolution and robustness with respect to environmental mismatch.

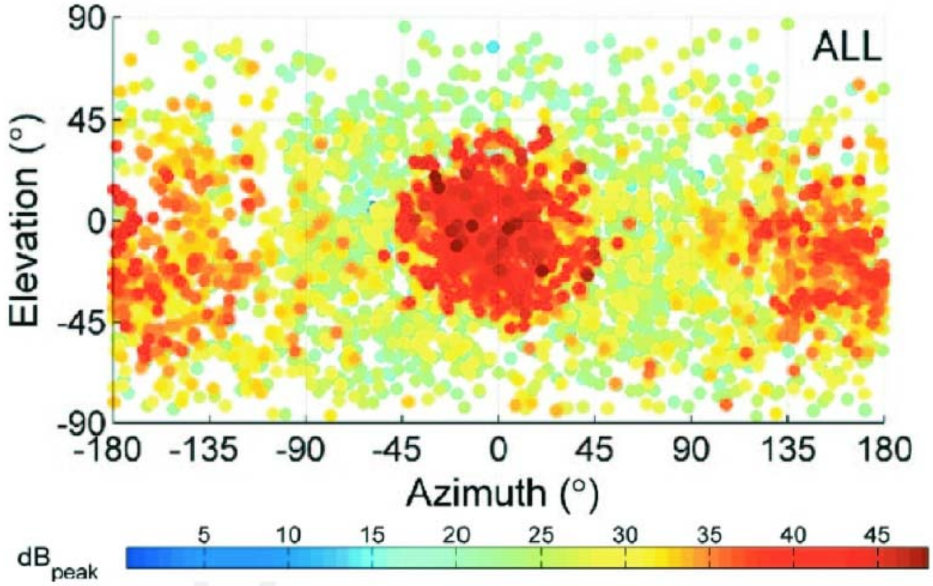

Figure 2. Estimated beam pattern of sperm whale clicks with level shown in color as a function of azimuth and elevation from the whale's main axis (which points from the tail to the rostrum). Receiver sensitivities were unknown, so these are not referenced levels but are relative such that 0 dB corresponds to the weakest recorded click. Recorded levels were corrected for transmission loss and are plotted with higher levels overlapping lower levels to minimize the effect of variable source levels. The clicks have a strong forward directed component and a weaker backward directed component.

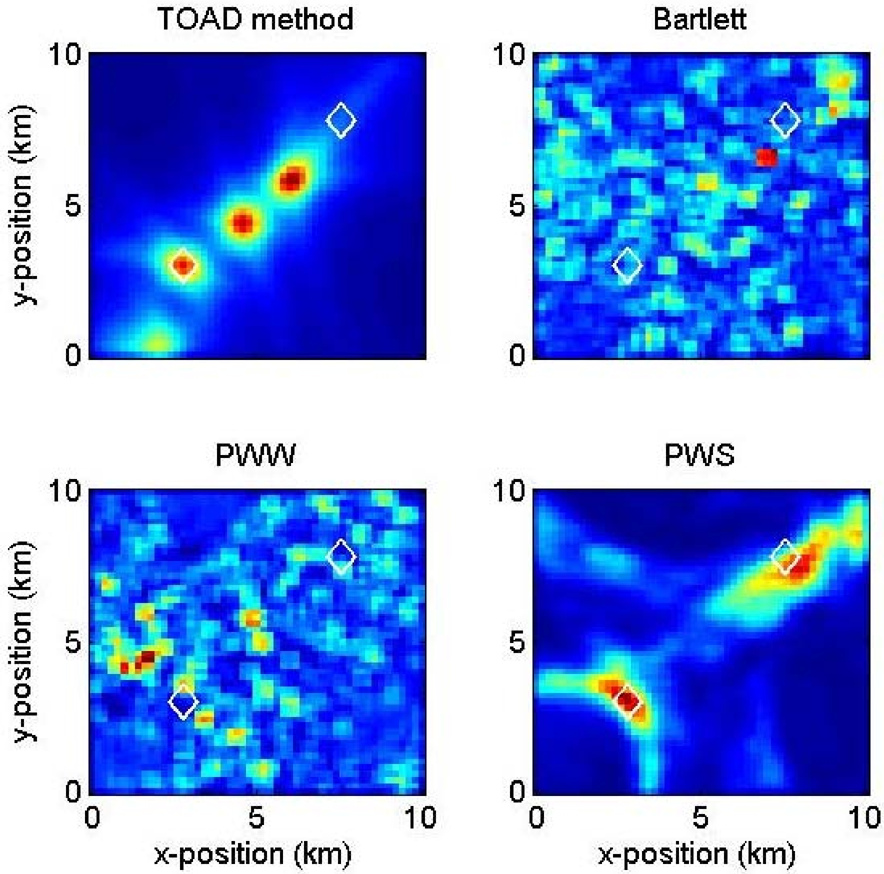

Figure 3. Plan view likelihood surfaces created using the time of arrival method (TOAD), Bartlett, PWW, and PWS processors. Correct source positions are shown as white diamonds. Data were simulated for two sources, three receivers, signal to-noise-ratio of –5 dB. Environmental mismatch was simulated by using an incorrect sound speed profile and bottom depth in the inversion (constant sound speed instead of the correct depth-dependent sound speed profile and 204 m depth instead of the correct depth of 200 m). Only the PWS processor correctly localizes both sources.

IMPACT/APPLICATIONS

Our localization methods are useful for monitoring and studying marine mammal behavior and for and mitigating human impact on marine mammals. They may be also be used to monitor the ocean environment for other undersea and sea-surface sound sources.

RELATED PROJECTS

LN Frazer and E-M Nosal are collaborating with Whitlow Au, (SOEST, HIMB) and Marc Lammers (Oceanwide Science Institute, Hawaii) on an ONR funded experiment to collect combined acoustic and visual data for validation of passive acoustic localization methods.

E-M Nosal is working with Jeff Polovina and Dave Johnston (NOAA, NMFS, Hawaii) on automated methods to detect, classify, and quantify boating/fishing and biological activity at Cross Seamount (~250 km south of Oahu) using data collected on a High-Frequency Autonomous Recording Package.

E-M Nosal is working with Roy Wilkens (SOEST) and Mike Richardson (Naval Research Lab, MS) to measure and model geo-acoustic properties of carbonate sediments in Kaneohe Bay, Hawaii.

E-M Nosal is working with Fred Duennebier and Roger Lukas (SOEST) to measure wind and rain noise characteristics using ALOHA hydrophone data (a bottom mounted cabled hydrophone ~100 km north of Oahu).

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